Thirty Years of Evolution of the Sedrun Landslide (Swisserland) from Multitemporal Orthorectified Aerial Images, Differential Digital Terrain Models and Field Data

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Abstract -**The 3D displacement fields of the Sedrun landslide located in Switzerland in the Grison canton have been computed for two periods (1973 to 1990 and 1990 to 2003) by combining Digital Terrain Models (DTM) differences and correlation of aerial ortho-images. The displacement fields, which are similar for the two periods, have been compared to the tectonic structures which exist at the surface of the landslide. Zones of major velocity gradient visible on displacement maps correspond to areas marked by strong brittle strain visible in the field. The landslide that currently moves at an average velocity of 10cm/y can be divided in four main parts based on characteristics of displacement field. The upper part is mainly in subsidence. The upper intermediate area shows an apparent uplift and a strong translation in the main slope. The lower intermediate field is in subsidence with a translation. The lower part of the landslide is in apparent uplift with a translation perpendicular to valley of the Drun Tobel. These particularities are discussed in terms of architecture and mechanisms of the landslide. The upper part subsides as a corner limited by normal faults. The intermediate part is affected mainly by toppling and the behaviour of the lower part suggests the existence of a decollement level. Ortho-image correlations and DTM differences appear as an efficient tool to constrain external and internal architecture of landslides.**

Keywords-Digital Terrain Models, Ortho-images, aerial photographs, velocity field, toppling, decollement level.

I. INTRODUCTION

Most of the current techniques for monitoring the displacements of slow velocity landslides (<1m/year) are based on the measurements of ground based reference stations. Conventional geodetic techniques (triangulation, tacheometry) and extensometry measurements are the most widely used [Angeli et al., 2000], with GPS surveys [Jackson et al., 1996, Malet et al., 2002, Squarzoni et al, 2005]. The data acquired using these techniques are only available for major landslides and are limited to the last 15 years for GPS data or 20 years for automatic laser tacheometry. Moreover, due to the spatial and temporal heterogeneities of ground deformations, such ground-based measurements are often not accurate enough to fully describe the velocity field of a landslide. These measurements also require additional human intervention on the landslide or in its vicinity.

Remote sensing imagery provides a powerful tool to measure landslide displacements because it offers a synoptic view of the area of interest that can be easily repeated in

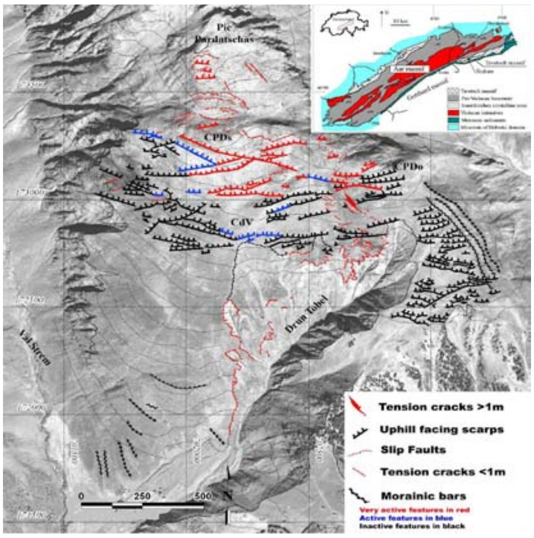

Figure 1: a) Geological setting and the localisation of the Sedrun landslide. b) Tectonic structures mapped on the Sedrun landslide from field investigation and aerial images analysis. Three main kinds of structures have been mapped: uphill facing scarps, normal faults and tension cracks.

time. Two main methods have been applied to remote sensing data: DInSAR including Permanent Scattering (Fruneau et al, 1996, Ferreti et al 2001, Squarzoni et al., 2004, Delacourt et al, 2007) and optical correlation. The optical correlation has been successfully used to monitor landslide displacements (Delacourt et al 2004, Casson et al. 2004), permafrost deformation and glacier flows (Kaab, 2002, 2008), and coseismic displacements (Leprince et al., 2007) from both aerial and satellite images. Aerial images have 3 main advantages. The spatial resolution is high (around or better than 1 meter), that is in good agreement with landslides of small extension. Furthermore, the aerial archive offers a good

temporal coverage in European countries. For example, the French territory is covered by aerial photographs since 1937 with a time span of about 5 years between two successive surveys, which are under the responsibility of IGN (the French National Geographic Institute). Finally, most of the aerial acquisitions are realized at the same epoch in order to minimize solar shadows variations. That is a great importance for optical correlation (Delacourt et al., 2004). Remote sensing techniques which can measure velocities up to some centimeters per day integrated on few days (DInSAR) to few years (optical correlation) are adapted to study the low velocity landslides which occur in bedrock.

The displacement field registered at the surface of landslides is a key parameter to understand the mechanics of the unstable masses (Casson et al, 2005). The behavior of a landslide is controlled by a combination of internal parameters, which are mainly the rheology and hydrology of the rock masses, and of external parameters, which are mainly geometric boundary conditions (topography, existence of a decollement level) and forcing climatic or seismic conditions. Various classifications of landslides have been proposed in literature (Hutchinson, 1968, Varnes, 1978, Cruden and Varnes, 1996, Hungr et al., 2001) depending on rock type and flow geometry and velocity. In case of sliding or rotation of strongly cohesive rock masses at low velocity, movements are produced by deformations that are distributed among many fractures of various sizes. These fractures can be localized at the base of the landslide and constitute a decollement level, or these fractures can be more or less vertical and limit rotating blocks. The questions, which need a response in that case, concern the depth of the possible decollement level and the depth reached by the fractures visible at the surface.

This paper presents an analysis of the Sedrun landslide (Grison canton - Switzerland) combining multitemporal orthorectified aerial images, differential Digital Terrain Model (DTM) and field data. The 3D surface velocity fields of the landslide are derived from aerial photographs for the periods 1973-1990 and 1990-2003. These velocity fields are discussed in terms of structural and mechanical behaviours of the landslide.

II. THE SEDRUN LANDSLIDE

The Sedrun landslide (fig. 1) is located in Switzerland in the Grison canton, on the left bank of the upper Rhine, just above and to the north of the villages of Sedrun and Chamischolas. This landslide is a major natural hazard because it threatens major infrastructures such as construction site for the Gotthard Tunnel (shaft for intermediate access), the Oberlap cantonal road, connecting the cantons of GrauBünden and Uri and a regional railway line connecting Zermatt to St. Moritz (Glacier Express). Furthermore, the village of Sedrun has been developed extensively over the last few decades, especially as a winter sport resort.

A. Geomorphologic and Geological Setting

The Sedrun landslide (fig. 1) is limited to the west by the Val Strem flood and to the south-east by the Drun Tobel flood. To the north, the landslide starts between the Cuolm Parlet Dadens (2452m) and the Piz Pardatschas (2665m). The unstable surface is around 140ha for a difference in height of 900m. It is marked mainly by a one kilometre wide plateau named Cuolm da Vi,which develops from 2200 to 2300m. The sliding rocks belong to the Tavetsch massif located between the crystalline alpine basement of the Aar and Gotthard Massifs (fig. 1). The Tavetsch massif is a long and narrow tectonic unit, which extends on 20km from east to west with a width of less than 4 km from Trun to Oberalp pass. This massif is separated from Aar to the north and Gotthard massif to the south by two major vertical faults (Wyder and Mullis, 1998). The massif is composed by metamorphic alpine rocks (Niggli, 1944), which have been submitted to variscan orogeny: paragneiss, paraschists, ultrabasites and pegmatite dykes. These metamorphic rocks are affected by a subvertical WSW-ENE foliation. Some fault breccias strike parallel to the regional schistosity. The unstable massif is crosscut by mylonitic shear zones, fault breccias and kakirites, which indicate that it has been submitted to high deformation from high temperatures to low ones.

B. Tectonic Analysis of the Landslide

The tectonic context has been analysed from classical aerial stereo photo-interpretation and field observations. The aerial images provided by SwissTopo have been acquired in 1990. Three main fault directions are visible on these images and have been mapped on figure 2. N170 striking faults border the landslide both to the east and to the west. The Val Strem is occupied by a major N170 fault. This direction is less visible at the east of the landslide but is clearly developed at the foot of the Culm Pardet Dado, just above the Drun Tobel catchments. The north of the landslide is limited by a N110 major fault which roughly separates the Cuolm Parlet Dadens from the Piz Pardatschas located to the north on a stable area. This N110 direction is visible in the upper part of the landslide under the Cuolm Parlet Dadens. A conjugate direction (N70) is also visible in the same area. This direction is less developed and marked by discontinuous faults. In the field, the N170 fault located at the east of the landslide is marked by a large 10 to 15 m width and 10m deep fresh crack. Other smaller cracks identically oriented are visible in the continuation of the major one, or parallel to it. The N110 direction is marked by the development of a 35m wide and 300m long fresh graben located at the foot of the Parlet Dadens (fig. 2). This N110 direction is also marked by the development of a 10m wide horst limited by two conjugated normal faults with a throw of at least 10m (fig. 2). Generally the N110 and N70 faults have uphill facing scarps. These scarps are sometimes filled by morainic products indicating that they are older than the last glacial period. Some of them affect the morainic cover indicating that they were active also after the end of the last glacial period.

C. History and Monitoring of the Landslide

Although population knew for decades that Cuolm da Vi was an unstable area, the beginning of the instability is not precisely dated. Various authors (Noverraz, 1998, Bonnard et al, 2004, Amann, 2006) studied the velocity of the landslide from tacheometric measurements, from GPS data and by visual inspection associated to stereomatching on 60 points picked on diachronic aerial images. They demonstrated that the landslide was already active in 1973. A permanent

tacheometric station has been installed in Sedrun in 2000. This station measures the distance of 25 points located on the landslide and one reference point located on the stable area. The measures indicate that the average velocity of the landslide has decreased from 2 cm/month in 2000 to 0.9 cm/month in 2005. The maximum velocity reached 5 cm/month at the top of the landslide, near the Culm Pardet Dadens at the beginning of the measurements. The velocity of the landslide increases in spring during the snowmelt. The landslide seems also very sensitive to rainy episodes (Bonnard et al., 2004).

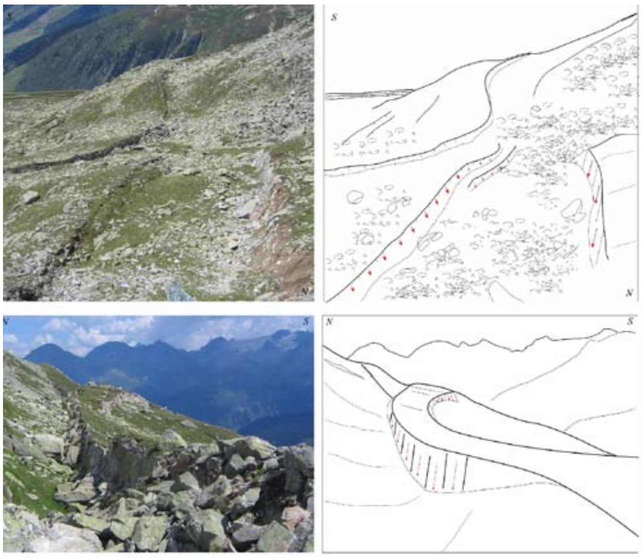

Figure 2: Field views of characteristic structures of the landslide. Top) Graben limited by two conjugated normal faults. Bottom) Horst limited by an uphill facing scarp.

III. DATA AND METHODOLOGY

Three stereoscopic pairs of aerial photographs acquired the 1973-09-04, the 1990-09-19 and the 2003-09-16 by SwissTopo have been used in this study. The images have been scanned with a photogrammetric scanner with a resolution of 1200 dpi which corresponds to approximate ground resolutions of respectively 25 cm, 27 cm and 44 cm.

In a first step, Digital Terrain Models (DTM) at a ground resolution of 1m have been processed in the Swiss Grid projection for each date of acquisition. Ground Control Points (GCP - points of the images whose cartographic coordinates are known) have been used in order to derive these absolute georeferenced DTM. These GCP's have been extracted from the Swiss 1/25 000 national topographic map. These GPC'a have been chosen on the stable area around the landslide. Then, the aerial images have been orthorectified and projected in the Swiss Grid reference system. The errors have been estimated by comparing the position of the GCP's measured on the Swiss 1/25 000 national topographic map and on the DTM and ortho-images. The vertical precision is better than 2 m. The planimetric errors are better than 2.8 m for the 1973 data, 2.1 m for the 1990 data and 2.3 m for the 2003 data. Both vertical and planimetric errors are always in the same direction for each temporal series of images. So, the vertical displacement measured on DTM is relevant if greater than 2 m. Horizontal displacements measured on ortho-images are significant if larger than 2.8 m.

The terrain elevation change can be determined by subtracting the coregistred DTM's. In case where no horizontal displacement occurred between acquisition dates, the difference between multitemporal DTM gives access to local vertical motion. However except for mining or pumping subsidence (Carnec and Delacourt, 2000) assumption of mono-component vertical displacement for land motion is not realistic. The planimetric component of motion has to be taken into account if a 3D motion occurred. This planimetric motion can be estimated by correlation of the multitemporal ortho-images. To measure the horizontal ground displacement in terms of direction and amount of displacement that occurred between two scenes acquired over the same area at two different times, a local window of a fixed number of pixels in width is defined on the oldest orthorectified image. Then, the corresponding window is searched on the more recent orthorectified image by maximizing a correlation function (Vadon et al., 2002). The starting point of the search is the expected position of the window if no displacement occurred between the two acquisitions. The measured shift is directly related to the ground displacement between the two acquisitions. The main parameters of the process are the size of the local window and the maximum displacement expected between the images. This process is iterated for each pixel of the oldest image. The result is composed of three arrays that have the size of the correlated images. The first one contains the shift in lines for each pixel, the second contains the shift in columns, and the third indicates the quality of the correlation.

This technique has already been successfully applied to map surface displacement related to earthquakes [Van Puymbroeck et al, 2000, Michel et al., 2002, Leprince et al., 2007], landslides [Delacourt et al., 2004, Casson et al 2005], glacier flow [Kaab, 2002, Kaab 2008] and volcanoes [De Michele, 2007]. The processing has been carried out using the MEDICIS correlator developed by CNES [Vadon et al, 2002]. This correlator uses FFT (Fast Fourier Transform) for the maximization of correlation ratio.

The two methods described above are complementary. Indeed, the DTM difference enables the zoning of the landslide based on apparent subsidence and uplift and the correlation of diachronic orthorectified images informs about the horizontal displacement of the landslide. The combination of the two methods produces a global 3D image of the displacement of the landslide.

IV. RESULTS

Multitemporal DTM differences (fig. 3) show that the landslide can be divided in 4 main zones from top to bottom with alternating apparent uplift and subsidence (called Up and Sb on Fig 3b). The domains with topographic variations of more than 2 m during the periods of 1973-1990 and 1990-2003 have been underlined. The value of 2 m corresponds to the elevation error of the DTM's. The zoning remains constant over the 2 periods. From top to bottom, the area located from Piz Pardatschas to Cuolm Parlet Dadens and the Cuolm Parlet Dado (Parlet crest) are in subsidence while the southern face of the Crest of the Parlet is in apparent uplift. The upper part of the plateau of Cuolm da Vi is also in

subsidence while the slopes located just under the plateau appear in uplift. The

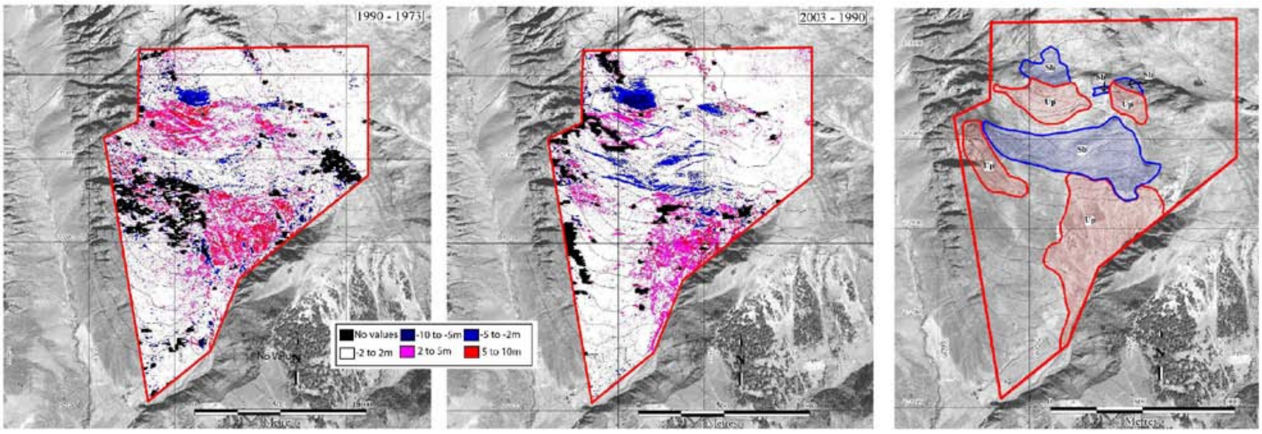

Figure 3: DTM differences maps for the two periods of time (1973-1990 and 1990 – 2003) and zoning of the landslide from the DTM difference results for the period 1990-2003. The landslide is affected by alternating zones of subsidence and apparent uplift. The zoning is the same for the period 1973-1990.

values of apparent uplifts and subsidence are larger than 25 cm/year for the Cuolm Parlet dadens and the Cuolm Parlet dado. The apparent subsidence of the upper part of the Plateau of Cuolm da Vi is less important and around 20 cm/year. This vertical displacement cannot be interpreted only in terms of vertical movements alone and must be associated to the horizontal displacement in order to be understood (Casson et al., 2005).

The correlation of orthorectified images shows that a global displacement occurs toward the south along the major slope of the topography (fig. 4). The velocity averaged on the surface of the landslide has increased from 10 cm/y in the period of 1973 to 1990 to 20 cm/y between 1990 to 2003. The zoning of the landslide is less obvious from the horizontal displacement data than from the vertical ones. The upper part of the landslide located between the Parlet crest and the Piz Pardatschas is affected by velocity ranging from 10 to 30 cm/y orientated from South-West to West. The Cuolm Parlet Dadens is the area with the fastest velocity, which ranges here from 30 to 50 cm/y toward the South in the main slope direction. The Cuolm Parlet dado which is located in the upper Eastern part of the landslide is affected by velocities ranging from 5 to 20 cm/y orientated toward the South-West. The plateau of Culm da Vi is affected by a motion ranging from 20 to 30cm/y. The orientation of the velocity vectors is toward the South in the upper part of the plateau. The velocity vectors rotate progressively toward the East and become nearly perpendicular to the Drun tobel Valley at the base of the Cuolm da Vi plateau.

The combination of both vertical and horizontal displacement values are presented in fig. 5. The landslide can finally be divided in 4 main domains. The “Dadens” zone corresponds to the domain surrounding the top of Cuolm Parlet dadens (A1, A4', A4, A2-3, A2-3', B1, B1', B2). The upper part is in subsidence and the southern flank is in translation (60 cm/yr) toward the South, with a small west component toward the Val Strem. The “Dado” zone corresponds to the top of Cuolm Parlet dado and its south-western slopes (Ht, Hs, H, Hg and H'). It shows a displacement pattern similar to the “Dadens” zone. The upper part is in subsidence (50 cm/y). The southern flank is in translation toward the south (15-25 cm/yr). The “Cuolm” zone corresponds to the plateau of Cuolm da Vi (B2, B2', E', C', and H'). This zone is affected by both subsidence (15-25 cm/yr) and translation (up to 20 cm/y) toward the south. Finally, the “Tobel” zone corresponds to right bank of Drun Tobel and the southern steep slopes located under of the plateau of Cuolm da vi (E, C, and D). This part shows a strong displacement (> 30 cm/yr) toward N 170 nearly perpendicular to thE DRUN TOBEL VALLEY.

V. DISCUSSION

A Meaning of the Measured Displacement Fields

Possible relationships between vertical movements observed from aerial images and displacement contexts are proposed in figure 6. The upper part of the landslide from Piz Pardatschas to the crest of Parlet is mainly affected by subsidence without noticeable horizontal displacements. In the field, this subsidence is associated to conjugated normal faults in the lower part of the pass and minor uphill facing scarps in the southern slope of the Piz Pardatschas. It corresponds to the case "subsidence" in figure 6. The crest of the Parlets is a region of apparent uplift and of large displacement toward the south associated at its base with a large uphill facing scarp (fig 1). The observed uplift results from a topographic effect associated to rotation toward the south of blocks limited by an uphill facing scarp. This interpretation is partly valid for the upper part of the plateau of Cuolm da Vi, which is in continuity with the southern slope of the crest of the Parlets. 100 to 200 m wide blocks elongated in the east west direction are limited by uphill facing scarps. This area is affected by subsidence and horizontal displacement toward the south. This case corresponds to "toppling" in figure 6. The southern part of plateau of Cuolm Da Vi is also active. It moves in a rather homogeneous way toward the south. The structures visible in this area seem to be inactive. That indicates that this area is affected by homogeneous translation with the dip of the topography larger than the dip of the decollement level (fig. 6). The rotation of the velocity vectors, which become perpendicular to the Drun Tobel signifies that the valley plays a role in the dynamics of the landslide. The domains,

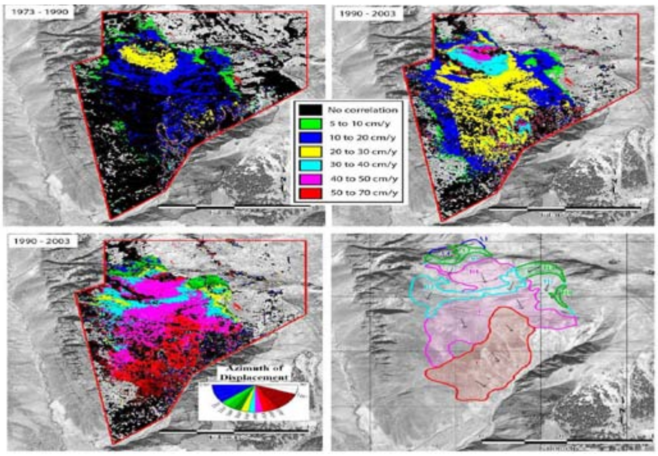

Figure 4: Ortho-image correlation for the two periods of study. The orientation of displacement vectors is shown for the period 1990 -2003. The zoning of landslide deduced from displacement results is shown for the period 1990-2003.

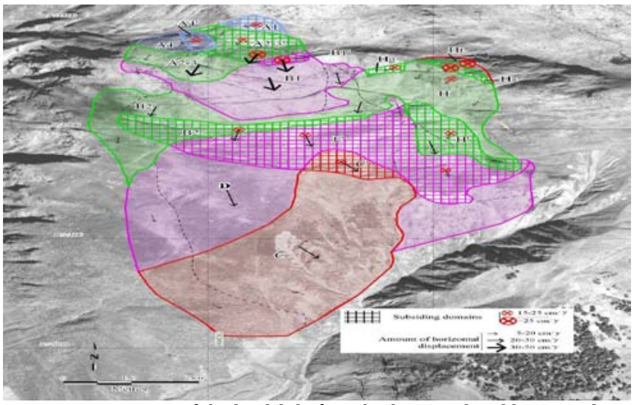

Figure 5: Zoning of the landslide from both vertical and horizontal components of velocity. See text for description.

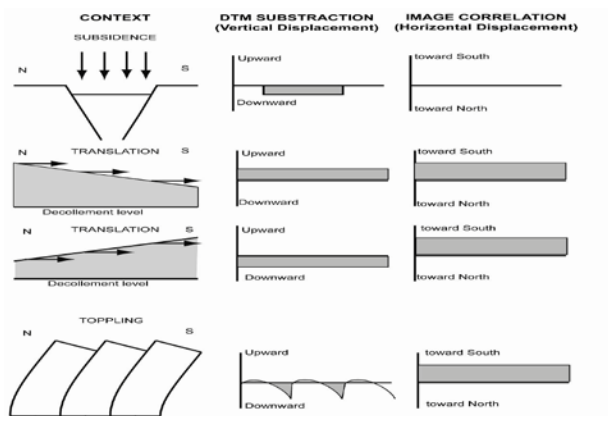

Figure 6: Schematic relationships between tectonic context and observed vertical and horizontal displacement. In case of displacement limited by rigid faults, the observed displacement is vertical, the horizontal displacement is negligible. In case of translation of a bloc along a decollement level, the vertical displacement is in apparent uplift if the dip of the topography is larger than the dip of the decollement layer. The vertical displacement appears in subsidence if the dip of the topography is lower than the dip of the decollement layer. The horizontal displacement is homogeneous in both cases. In case of toppling, the average vertical displacement is in subsidence. However, the summit of blocs can show an apparent uplift which results from the translation of the topography.

which belong to the top of the right bank of the Drun Tobel valley, are affected by numerous superficial landslides, which make the image correlation impossible.

Most of the structures observed in the field are compatible with the displacements measured from remote sensing techniques. Brittle structures observed in the field (for example figure 2) correspond to velocity discontinuities and thus to zones of major strain. The freshness of the cracks observed in the field reveals the activity of the structures. Some cracks, whose surface is altered, are clearly old. Some others show clearly traces of reactivation with mirrors that are altered in their upper part and fresh in their lower part. Finally, some cracks are clearly recent as the mirrors are fresh. Image correlations show zones, which are inactive despite the freshness of the cracks. That could indicate that the crack openings are episodic.

B. Conceptual Model of the Landslide of Sedrun (fig. 7)

The Sedrun landslide is clearly divided in several blocks that have to be discussed relative to the deep behaviour of the massif. The upper part of the landslide is mainly affected by subsidence in the pass located behind the crest of Parlets. The horizontal velocity of this area is low and oriented toward the South West. This area is thus a zone of major subsidence delimited by conjugated faults or shear zones, which are visible in the field and on the aerial images (fig. 7a). The crest of Parlets is an area of apparent uplift ad of high translation toward the South marked by uphill facing scarps. This area can correspond to a major toppling. But as the topographic slope is strong (more than 25°) on both sides of the crest of Parlets and the horizontal displacement between the two acquisitions is important (more than 10m), DTM difference will exhibit a significant signal, which can be interpreted as uplift. The upper part of the plateau of Cuolm da Vi displays the same feature than the crest of the Parlets except that it is in subsidence. This area is also affected by toppling. The topographic slope is less pronounced than the topographic slope of the crest of Parlets. That can explain the subsidence. The lower part of the landslide is affected by homogeneous velocity, which becomes progressively perpendicular to the Drun Tobel valley. The brittle structures visible at the surface are inactive. The area is in apparent uplift. These observations can be explained by a global translation along a decollement level. However, there is no evidence of the emergence of a decollement level in the Drun Tobel. This decollement level could be deeper than the depth of the valley (around 200m) or hidden by active erosion occurring in the Drun Tobel. This conceptual model has now to be tested against a numerical mechanical model.

VI. CONCLUSION

3D surface displacement fields of the Sedrun landslide have been derived by combining multitemporal DTM difference and correlation of ortho-images. This landslide can be divided in 4 parts according to the 3D displacement fields. The upper part is in subsidence. The crest of Parlet displays an apparent uplift and a strong translation toward the South, in the main slope of the landslide. This part is affected by toppling. The plateau of Cuolm da Vi is in subsidence and is also submitted to a strong translation toward the South. It is

also certainly affected by toppling as suggested by the numerous uphill-facing scarps perpendicular to the slope. The lower part of the landslide is affected by apparent uplift and translation, which is perpendicular to the Drun Tobel valley. This suggests that this area is affected by a translation, which is accommodated on a blind decollement level. This work has shown that difference between DTM and correlation of ortho-images is a powerful tool to measure the complete 3D displacement of a landslide with a time step of several years. This 3D displacement field associated with field observations help to suggest conceptual models of landslide deep architecture. The conceptual model proposed for the Sedrun landslide has now to be tested against numerical mechanical models.

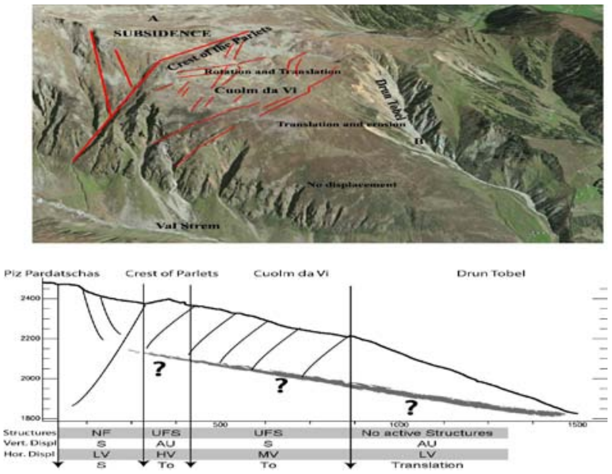

Figure 7: Aerial image draped on DTM. A and B are the limits of the section. Conceptual model of the Sedrun landslide based on both vertical and horizontal component of displacement and structures observed in the field (Structures : NF - Normal Faults, UFS - Uphill Facing Scarps. Vertical displacement: S – Subsidence, AU - Apparent Uplift. Horizontal Displacement: LV - Low Velocity, HV- High Velocity, MV - Medium Velocity. Interpretation : S – Subsidence, To - toppling. A possible decollement level is indicated under the Cuolm da Vi plateau.

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